Digital Filter Box
User Manual

With Moku:Lab's Digital Filter Box, you can interactively design and generate different types of infinite impulse response filters with output sampling rates of 122 kHz and 15.625 MHz. Select between lowpass, highpass, bandpass and bandstop filter shapes with up to eight fully configurable types including Butterworth, Chebyshev and Elliptical.

LIQUID INSTRUMENTS

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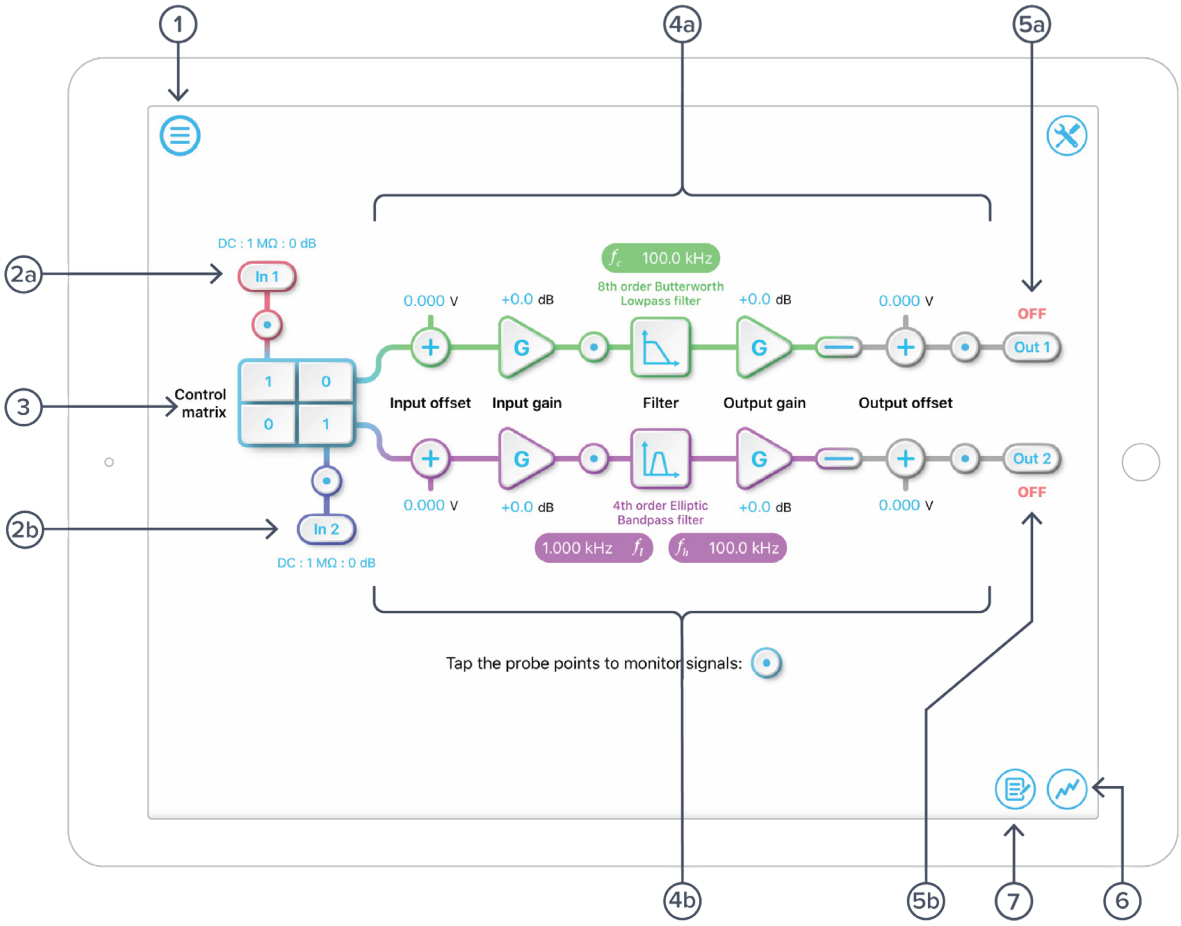
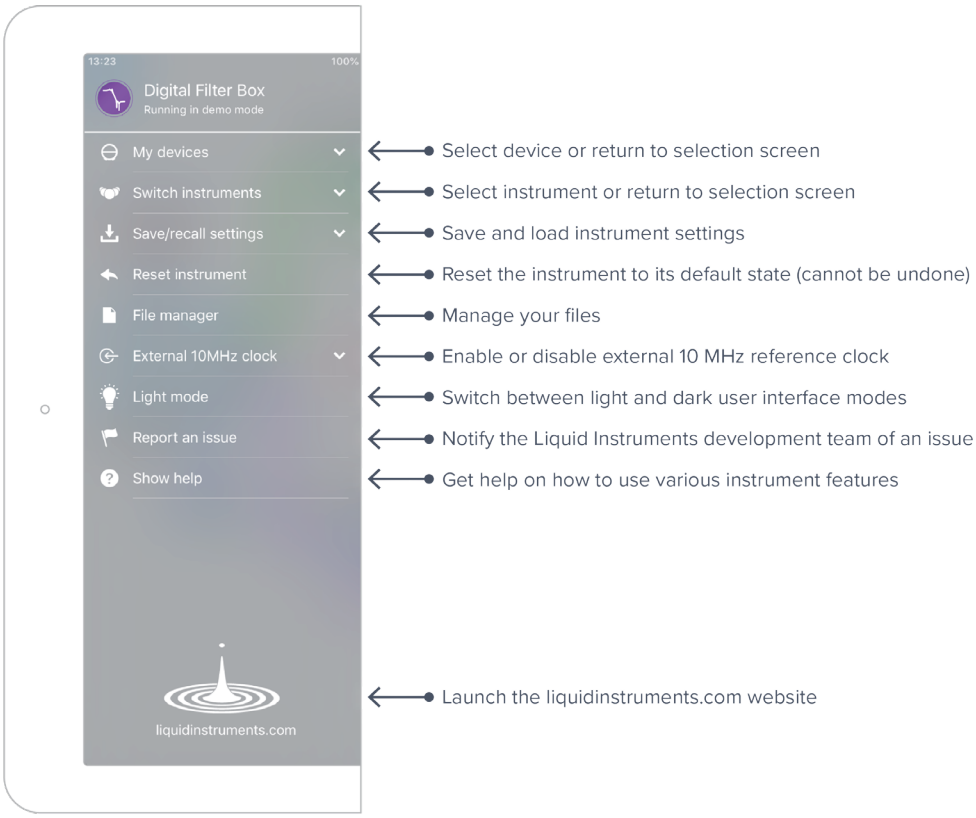
User Interface



ID	Description
1	Main menu
2a	Input configuration for Channel 1
2b	Input configuration for Channel 2
3	Control matrix
4a	Configuration for Filter 1
4b	Configuration for Filter 2
5a	Output switch for Filter 1
5b	Output switch for Filter 2
6	Enable the oscilloscope
7	Enable the datalogger

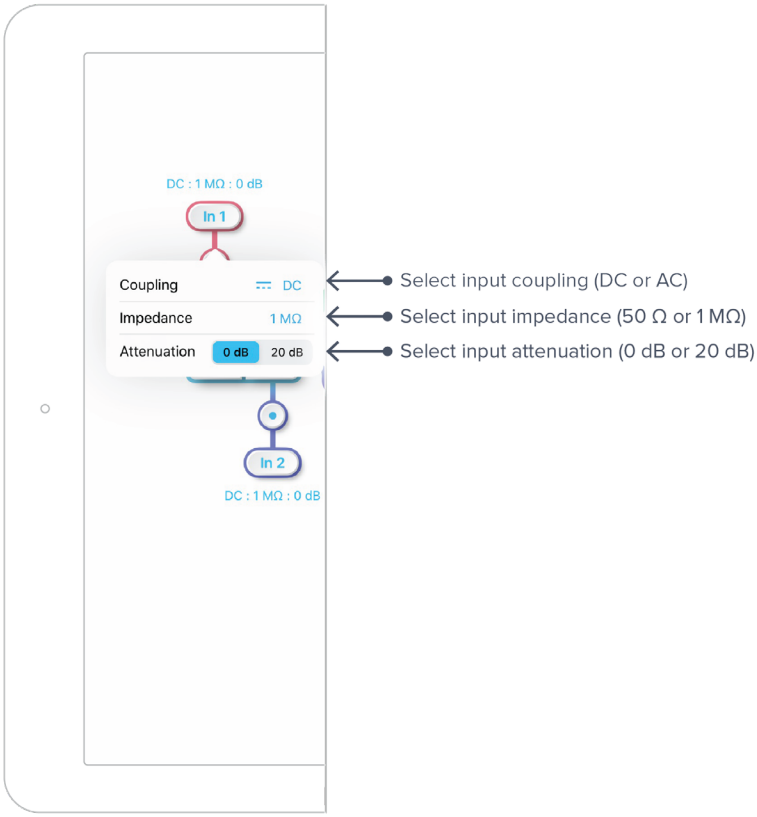
Main Menu

The **main menu** can be accessed by pressing the icon, allowing you to:



Input Configuration

The **input configuration** can be accessed by tapping the In 1 or In 2 icon, allowing you to adjust the coupling, impedance, and input range for each input channel.



Details about the probe points can be found in the Probe Points section.

Control Matrix

The **control matrix** combines, rescales, and redistributes the input signals to the two independent digital filters. The output vector is the product of the control matrix multiplied by the input vector.

$$\begin{bmatrix} Path1 \\ Path2 \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \times \begin{bmatrix} In1 \\ In2 \end{bmatrix}$$

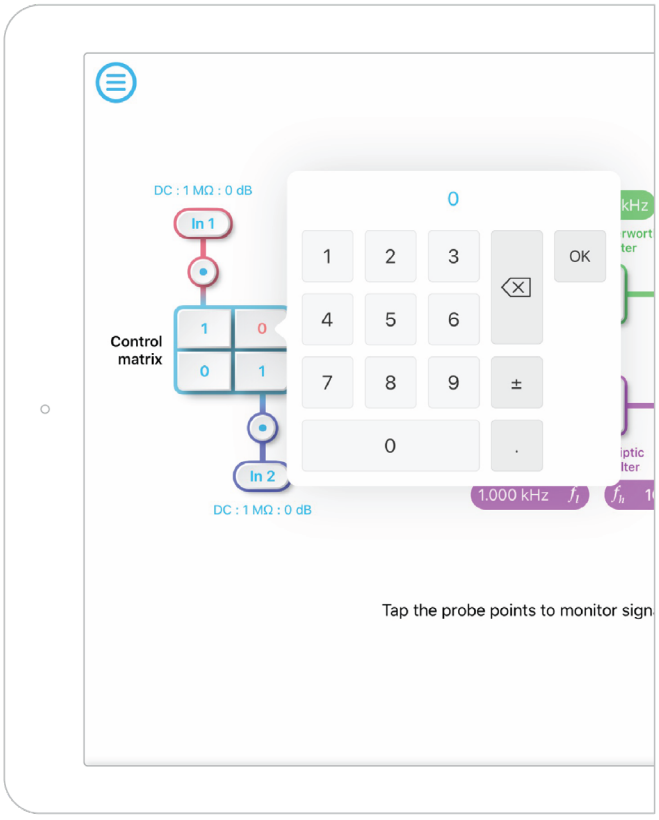
where

$$Path1 = a \times In1 + b \times In2$$

$$Path2 = c \times In1 + d \times In2$$

For example, a control matrix of $\begin{bmatrix} 1 & 1 \\ 0 & 2 \end{bmatrix}$ adds Input 1 and Input 2 and routes to the top *Path1* (Digital Filter 1); multiples Input 2 by a factor of two, and then sends it to the bottom *Path2* (Digital Filter 2).

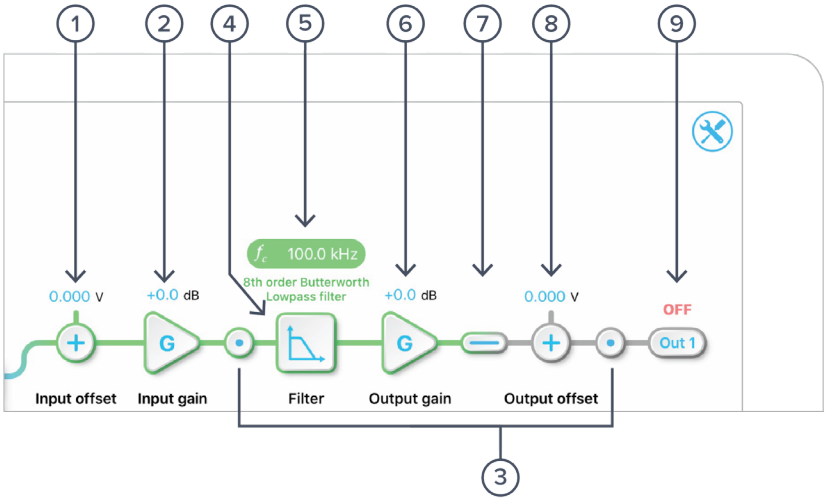
The value of each element in the control matrix can be set between -20 to +20 with 0.1 increments when the absolute value is less than 10, or 1 increment when the absolute value is between 10 and 20. Tap the element to adjust the value.



Digital Filter

The two independent, fully real-time configurable digital filter paths follow the control matrix in the block diagram, represented in green and purple for filter 1 and 2, respectively.

User Interface

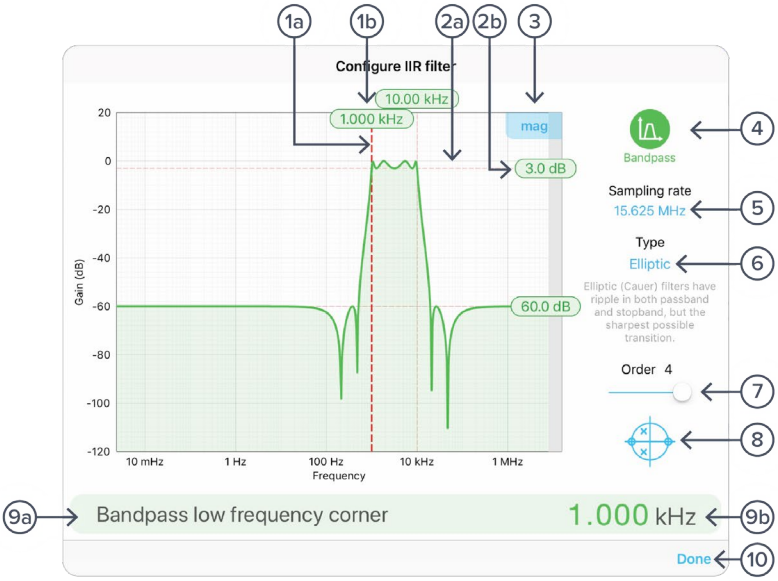


ID	Parameter	Description
1	Input offset	Tap to adjust the input offset (-1 to +1 V).
2	Input gain	Tap to adjust the input gain (-40 to 40 dB).
3	Probe points	Tap to enable/disable the probe points. See Probe Points section for details.
4	Digital filter	Tap to view and configure the digital filter builder.
5	Quick filter control	Tap or slide to quickly adjust the filter settings
6	Output gain	Tap to adjust the input gain (-40 to 40 dB).
7	Output switch	Tap to zero the filter output.
8	Output offset	Tap to adjust the output offset (-2 to +2 V).
9	DAC switch	Tap to enable/disable Moku:Lab's DAC output.

Digital Filter Builder

Filter Builder Interface

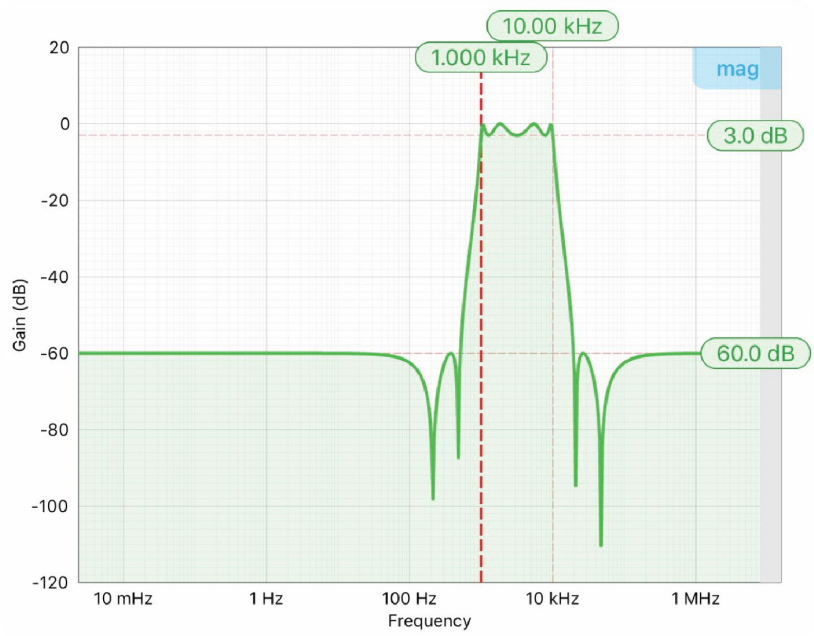
Tap the  icon to open the filter builder view.



ID	Parameter	Description
1a	Frequency (horizontal) cursor	Cursor for corner frequency.
1b	Cursor reading	Reading for frequency cursor. Drag to adjust the corner frequency. Tap to manually enter corner frequency.
2a	Gain (vertical) cursor	Cursor for ripple/gain/attenuation level.
2b	Cursor reading	Reading for gain cursor. Drag to adjust the gain/ripple level. Tap to manually enter passband ripple.
3	Display toggle	Toggle between magnitude and phase response curve.
4	Filter shape selection	Tap to select between lowpass, highpass, bandpass, bandstop, and custom filters.
5	Sampling rate	Tap to select between 15.625 MHz or 122.07 kHz.
6	Filter type selection	Tap to select between Butterworth, Chevyshev I/II, Elliptic, Bessel, Gaussian, Cascaded or Legandre filters.
7	Filter order	Slide to adjust filter orders.
8	s-plane plot	Tap to view the filter poles and zeros in s-plane.
9a	Active configurable parameter	Name of the active configurable parameter.
9b	Parameter value	Tap to manually enter the active configurable parameter value.
10	Save and close	Tap to save and close the filter builder.

Filter Response Plot

The Filter Response Plot provides an interactive representation (gain as a function of frequency) of the filter.



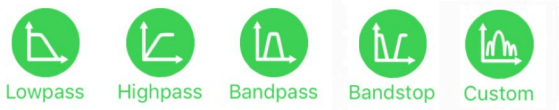
The green/purple solid curve represents the active response curve for Digital Filter 1 and 2, respectively.

The bold red dashed line represents the cursor for the actively selected parameter.

The red dashed lines represent other user editable cursors.

Filter Shapes

The shape of the filter can be selected by pressing the ④ button (on Page 9). There are four pre-defined filter shapes and a fully customizable filter option.



Sampling Rates

Users can select a high (15.625 MHz) or a low (122.07 kHz) output sampling rate mode based on the desired corner frequencies. The following table summarizes the lower and upper bounds for each shape of pre-defined filters with different sampling rates:

Shape	Sampling Rate	Minimum corner frequency	Maximum corner frequency
Lowpass	Low	23.45 mHz	54.93 kHz
	High	3.002 Hz	7.031 MHz
Highpass	Low	289.5 mHz	54.93 kHz
	High	37.05 Hz	7.031 MHz
Bandpass	Low	1.221 Hz	54.93 kHz
	High	156.3 Hz	7.031 MHz
Bandstop	Low	23.45 mHz	54.93 kHz
	High	3.002 Hz	7.031 MHz

Filter Types

The type of filter can be selected by pressing the ⑥ button (on Page 9). There are seven pre-defined filter types with user-selectable filter orders from 2 up to 8, depending on the filter shapes.

Filter Types	Description
Butterworth	Butterworth filters have a maximally flat passband and a monotonic frequency response.
Chebyshev I	Chebyshev I filters have ripple in the passband but a sharper transition than Butterworth filters.
Chebyshev II	Chebyshev II filters have ripple in the stopband but a sharper transition than Butterworth filters.
Elliptic	Elliptic (Cauer) filters have ripple in both passband and stopband, but the sharpest possible transition.
Cascaded	Cascaded first-order filters have zero overshoot in the time domain.
Bessel	Bessel filters have a maximally flat group and phase delay in the passband, thus preserving the wave shape of passed signals.
Gaussian	Gaussian filters have the minimum possible group delay, and a step response with no overshoot and minimum rise and fall time.
Legendre	Legendre (Optimum L) filters have the sharpest possible transition while maintaining a monotonic frequency response.

Filter Orders

For single sided filters, the order of the filter can be selected between 2, 4, 6, and 8. For double sided filters, the order of the filter can be selected between 2 and 4.

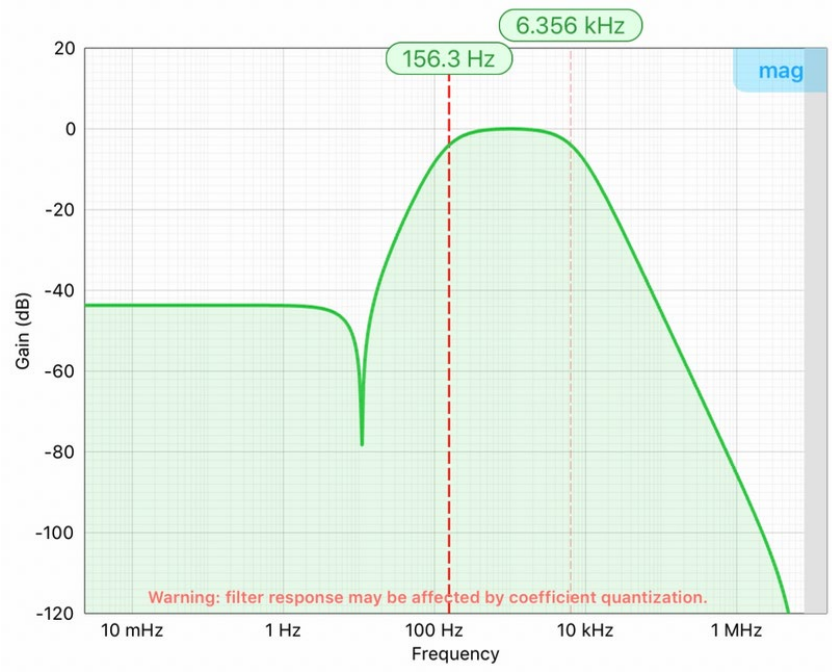
Ripples

Chebyshev I, II, and Elliptic filters have ripples on either passband, stopband or both. The following table summarize the adjustable range for the passband and stopband ripples for these filter types.

Filter Types	Passband Ripple	Stopband Ripple
Chebyshev I	0.1 dB to 10.0 dB with 0.1 dB increment	N/A
Chebyshev II	N/A	10.0 dB to 100.0 dB with 1 dB increment
Elliptic	0.1 dB to 10.0 dB with 0.1 dB increment	10.0 dB to 100.0 dB with 1 dB increment

Coefficient Quantization

Due to the limit of digitization depth, the quantization error is pronounced at certain FIR filter settings. A red coefficient quantization warning may appear on the bottom of the response plot.



Custom Filter

The custom filter implements infinite impulse response (IIR) filters using 4 cascaded Direct Form I second-order stages with a final output gain stage. The total transfer function can be written:

$$H(z) = g\prod_{k=1}^{4} s_k \frac{b_{0k} + b_{1k}z^{-1} + b_{2k}z^{-2}}{1 + a_{1k}z^{-1} + a_{2k}z^{-2}}$$

To specify a filter, you must supply a text file containing the filter coefficients on Moku:Lab's SD card or iPad storage. The file should have six coefficients per line, with each line representing a single stage. If output scaling is required, this should be given on the first line:

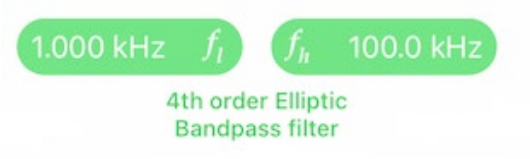
g (optional)	7.8357416974,					
Stage 1	1.0000000000,	0.0044157497,	0.0088314994,	0.0044157497,	-1.6692917152,	0.9692269375
Stage 2	1.0000000000,	0.0472217267,	0.0944434535,	0.0472217267,	-1.8988580275,	0.9341904809
Stage 3	1.0000000000,	0.0375275838,	0.0750551677,	0.0375275838,	-1.9259771042,	0.9311308010
⋮	s	b_0	b_1	b_2	a_1	a_2

Each coefficient must be in the range [-4.0,+4.0). Internally, these are represented as signed 48-bit fixed-point numbers, with 45 fractional bits. The output scaling can be up to 8,000,000. Filter coefficients can be computed using signal processing toolboxes in e.g. MATLAB or SciPy.

Some coefficients may result in overflow or underflow, which degrade filter performance. Filter responses should be checked prior to use.

Quick Filter Control

This panel (⑤) allows users quickly to view and adjust the filter parameters without opening the full filter builder.



Tap the icon (i.e. 

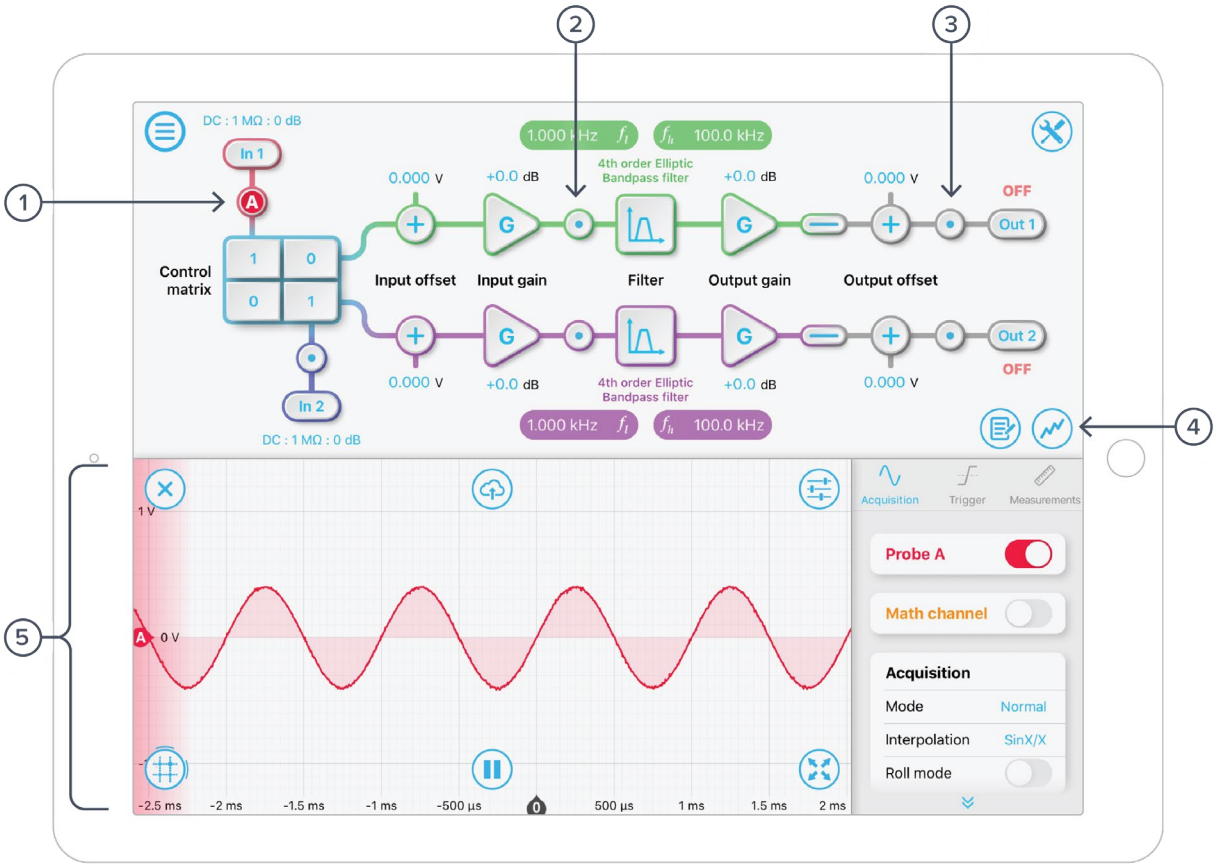
) to enter the value. Hold and slide to adjust the value.

ID	Description
f_l	Low frequency corner
f_h	High frequency corner

Probe Points

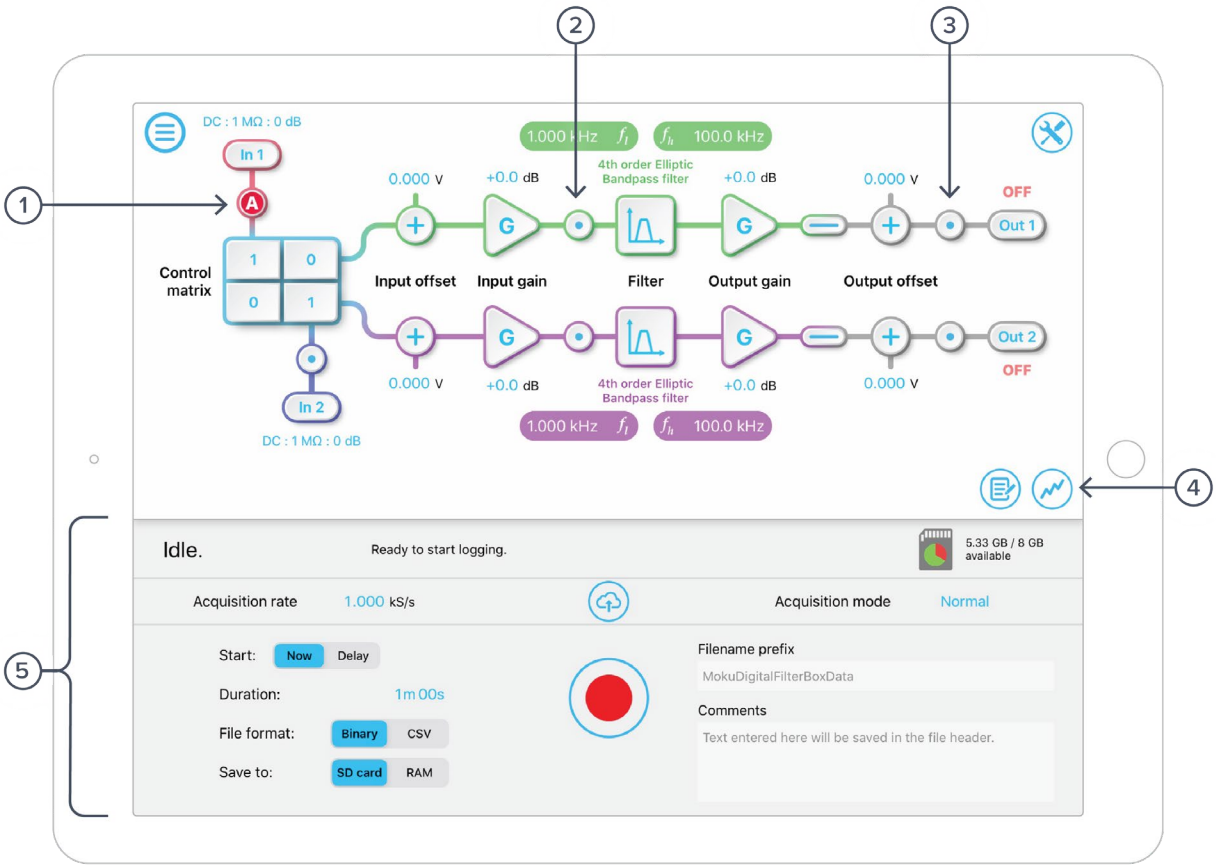
Moku:Lab's Digital Filter Box has an integrated oscilloscope and data logger that can be used to probe or record the signal at the input, pre-filter, and output stages. The probe points can be added by tapping the icon.

Oscilloscope



ID	Parameter	Description
1	Input probe point	Tap to place the probe point at inputs.
2	Pre-Filter probe point	Tap to place the probe before the filter.
3	Output probe point	Tap to place the probe at outputs.
4	Oscilloscope/data logger toggle	Toggle between built-in oscilloscope or data logger.
5	Oscilloscope	Refer to **Moku:Lab's Oscilloscope** manual for the details.

Data Logger



ID	Parameter	Description
1	Input probe point	Tap to place the probe point at inputs.
2	Pre-Filter probe point	Tap to place the probe before the filter.
3	Output probe point	Tap to place the probe at outputs.
4	Oscilloscope/data logger toggle	Toggle between built-in oscilloscope or data logger.
5	Data Logger	Refer to **Moku:Lab's Data Logger** manual for the details.

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